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Probing MACHOs by observation of M31 pixel lensing with the 1.5m Loiano telescope

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Abstract. We analyse a series of pilot observations in order to study microlensing of (unresolved) stars in M31 with the 1.5m Loiano telescope, including observations on both identified variable source stars and reported microlensing events. We also look for previously unknown variability and discover a nova. We discuss an observing strategy for an extended campaign with the goal of determining whether MACHOs exist or whether all microlensing events are compatible with lens stars in M31.

Key words. Gravitational lensing - Galaxy: Halo - Galaxies: M31

1. Introduction

Following the original proposal of Paczyński (1986), several microlensing campaigns have been undertaken in the recent years with the purpose of unveiling the content of galactic halos in form of MACHOs. While both the MACHO (Alcock et al. 2000) and EROS (Tisserand et al. 2006) groups have published comprehensive results of their respective campaigns, and an analysis of the OGLE campaign is underway, no consensus has yet been reached on either the density of MACHOs or their mass spectrum, and it is still not clear whether "self lensing" within the Magellanic Clouds (Sahu 1994; Wu 1994) can account for most or even all of the detected microlensing events (Belokurov et al. 2003, 2004; Mancini et al. 2004; Griest & Thomas 2005; Bennett 2005; Calchi Novati et al. 2006; Evans & Belokurov 2006).

Searching for microlensing events towards the Andromeda Galaxy (M31) not only allows one to monitor a huge number of stars ($\sim 10^8$) within a few fields, but also allows one to fully probe M31's whole halo (which is not possible for the Milky Way), and possibly to distinguish more easily between self lensing and lensing by MACHOs because M31's tilt with respect to the line of sight induces a characteristic signature in the spatial distribution of the halo events (Crotts 1992; Baillon et al. 1993; Jetzer 1994). Observational campaigns have been carried out by several collaborations: AGAPE (Ansari et al. 1997, 1999), Columbia-VATT (Crotts & Tomaney 1996), POINT-AGAPE (Aurière et al. 2001; Paulin-Henriksson et al. 2003), SLOTT-AGAPE (Calchi Novati et al. 2002, 2003), WeCAPP (Riffeser et al. 2003), MEGA (de Jong et al. 2004), NainiTal (Joshi et al. 2005) and ANGSTROM (Kerins et al. 2006). The detection of a handful of microlensing candidates have been reported and first, though contradictory, conclusions on the MACHO content along this line of sight have been reported (Calchi Novati et al. 2005; de Jong et al. 2006).

In order to go beyond these first results, it is essential to choose an appropriate observational strategy for the new observational campaigns. Indeed, the experience of the previous campaigns shows that a careful assessment of the characteristics of the microlensing signal and of potentially contaminating stellar variables is crucial. Two main phenomenological characteristics of microlensing events

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must be taken into account: the duration and the flux deviation (e.g. Ingrosso et al. 2006a,b). Microlensing events in M31 are expected to last only a few days (this holds in the lens mass range $10^{-2} - 1\ \mathrm{M}_\odot$, over which self lensing but also most of the MACHO signal is expected). Note that here we refer to the full-duration-at-half-maximum, $t_{1/2}$, easily evaluated out of pixel lensing observations, with $t_{1/2} = t_{1/2}(t_\mathrm{E}, u_0)$, where t_E, u_0 are the *Einstein time* and impact parameter, respectively. The degeneracy in the parameter space t_E, u_0 is intrinsically linked to the fact that the underlying sources are not resolved objects so that the background level of the light curves is a blend (of a huge number) of stars (Gould 1996). However, as was shown to be the case for some of the POINT-AGAPE microlensing candidates, extremely good sampling along the flux variation sometimes allow one to break this degeneracy. To gain insight into the underlying mass spectrum of the lens population (recall $t_\mathrm{E} \propto \sqrt{M_\mathrm{lens}}$), it will be essential to break the t_E, u_0 degeneracy beyond what was achieved in previous campaigns. Furthermore, the expected short duration can also be used to robustly test the detected flux variations with respect to the variable star background (Calchi Novati et al. 2005), but to achieve this, a very tight and regular sampling is again necessary. On the other hand, the expected duration implies that to characterise the microlensing signals, the campaign does not need to be extremely long. Besides, the dataset of previous campaigns already allows one to check for the expected uniqueness of microlensing signals. The long time baseline can then be exploited in order to increase the expected rate of events. Very tight and regular sampling on a nightly basis is therefore a first crucial feature for an optimal observational strategy. This would represent an important improvement with respect to previous campaigns that would allow one both to better distinguish microlensing events from other background variations, and, possibly, to break some of the degeneracy in the microlensing parameter space. As for the flux deviation, the main results have been obtained using the 2.5m INT telescope with integration times of about 20 minutes per night, so that even smaller telescopes can be used, provided that long enough integration times are employed to reach the needed signal-to-noise ratio.

In this paper we present the results of the pilot season of a new observational campaign towards M31 carried out with the Loiano telescope at the "Osservatorio Astronomico di Bologna" (OAB)[1]. In Sect. 2 we present the observational setup and outline data reduction and analysis. In Sect. 3 we present the results of our follow-up observations on previously reported microlensing candidates and other variable light curves, and we report the discovery of a new Nova variation. In Sect. 4 we estimate the expected microlensing signal and discuss the feasibility and objectives of a longer-term microlensing campaign.

[1] http://www.bo.astro.it/loiano/index.htm

2. Data analysis

2.1. Observational setup, data acquisition and reduction

As pilot observations for studying microlensing of stars in the inner M31 region, we observed two fields during 11 consecutive nights, from 5 September to 15 September 2006, with the 152cm Cassini Telescope located in Loiano (Bologna, Italy). We make use of a CCD EEV of 1300x1340 pixels of $0.''58$ for a total field of view of $13' \times 12.'6$, with gain of 2 e^-/ADU and low read-out noise (3.5 e^-/px). Two fields of view around the inner M31 region have been monitored, centered respectively at RA=0h42m50s, DEC=41°23′57″ ("North") and RA=0h42m50s, DEC=41°08′23″ ("South") (J2000), so as to leave out the innermost ($\sim 3'$) M31 bulge region, and with the CCD axes parallel to the north-south and east-west directions, in order to get the maximum field overlap with previous campaigns (Fig. 1). To test for achromaticity, data have been acquired in two bandpasses (similar to Cousins R and I), with exposure times of 5 or 6 minutes per frame. Overall we collected about 100 exposures per field per filter over 8 nights or about 15 images per night[2]. Typical seeing values were in the range $1.5'' - 2''$. Bias and sky flats frames were taken each night and standard data reduction was carried out using the IRAF package[3]. We also corrected the I-band data for fringe effects.

2.2. Image analysis

The search for flux variations towards M31 has to deal with the fact that sources are not resolved objects, so that one has to monitor flux variations of every element of the image (the so called "pixel-lensing" technique discussed in Gould 1996). As for the preliminary image analysis, we follow closely the strategy outlined by the AGAPE group (Ansari et al. 1997; Calchi Novati et al. 2002), in which each image is geometrically and photometrically aligned relative to a reference image. To account for seeing variations we then substitute for the flux of each pixel, the flux of the corresponding 5-pixel square "superpixel" centered on it (whose size is determined so as to cover most of the average seeing disc) and then apply an empirical, linear, correction in the flux, again calibrating each image with respect to the reference image. The final expression for the flux error accounts both for the statistical error in the flux count and for the residual error linked to the seeing correction procedure. Finally, in order to increase the signal-to-noise ratio, we combine the images taken during the same night.

[2] During the last useful night only a few R images in the North field could be taken.

[3] http://iraf.noao.edu/

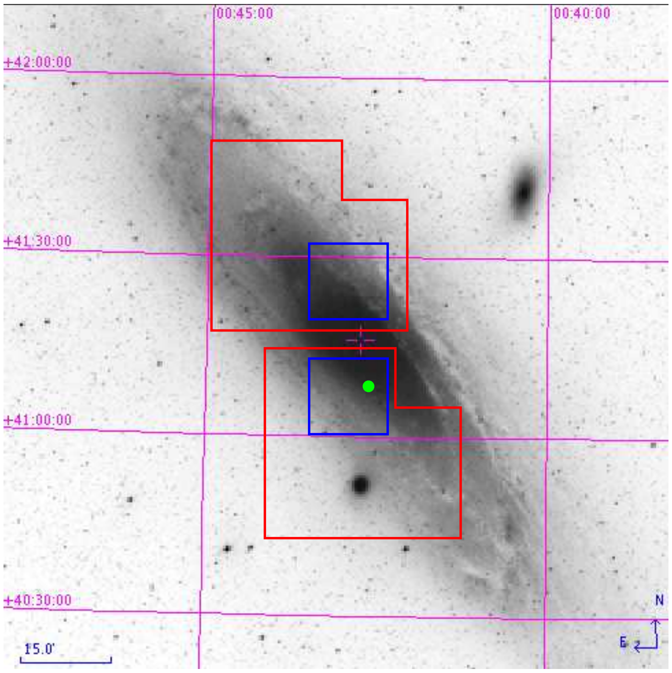

Fig. 1. Projected on M31, we display the boundaries of the two 13'x12.6' monitored fields (inner contours), together with the larger INT fields and the centre M31 (cross). The filled circle marks the position of the Nova variable detected (Sect. 3.3).

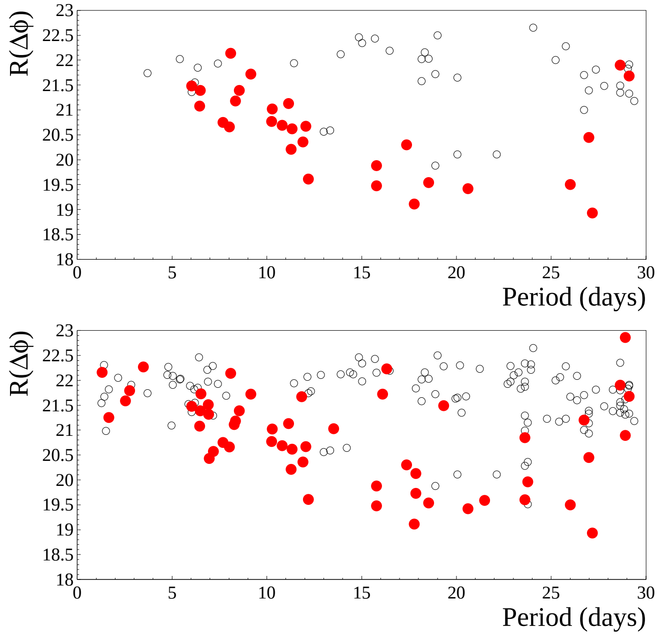

Fig. 2. $R(\Delta\phi)$ vs. Period for short-period ($P < 30$ d) variable stars reported in the POINT-AGAPE catalogue (top panel shows the subset with $\log(L_f) < -30$), where filled circles indicate the flux variations identified within the OAB data set.

3. Light curve results

3.1. Variables in the POINT-AGAPE catalogue

In order to assess the quality of the present data set as compared to that of previous campaigns we looked into observations of ~ 40000 stars identified as variables by the POINT-AGAPE group (An et al. 2004). Besides the position, each variation in this catalogue is characterised by three quantities: the magnitude corresponding to the flux deviation at maximum $R(\Delta\phi)$, with values down to $R(\Delta\phi) \sim 23$, the period (P) as evaluated using a Lomb algorithm, and an estimator of the probability of a false detection (L_f) (high absolute values of L_f indicate a sure identification). We note that most of the variations in the catalogue are rather faint and only a few have short periods.

We want to investigate which fraction of variables found by POINT-AGAPE can be identified by our observations. (Preliminary to the analysis, we must evaluate the relative geometrical and photometrical transformation between the two data sets. In particular, we find that $\sim 30\%$ of the original sample belongs also to our field of view). Since our observations cover only 11 days, we restrict our attention to the shortest periods ($P < 30$ d), which encompasses a $\sim 2\%$ subset of the POINT-AGAPE catalogue. Note that our limited baseline does not allow us to properly characterise the shape parameters of the detected variations. Therefore, in order to cross-identify the flux variations detected with those belonging to the POINT-AGAPE catalogue we only test for the offset between the position evaluated through our selection and the transformed POINT-AGAPE position.

For our analysis, we first identify a "clean" set of variable stars (selected by demanding $\log(L_f) < -30$), which includes $\sim$ 25% of the POINT-AGAPE sample. Restricting ourselves to short-period variables with $P < 30$ d, leaves us with 169 stars within our field of view, among which 68 fall into the "clean" sample. For the latter, we detect most of the bright variations ($R(\Delta\phi) < 21$), namely $\sim 70\%$, and about 40% of all of the variations. When we consider the total sample of short-period variables we arrive at values that are about 10% smaller. This partly results from the fact that the total sample contains a larger fraction of faint objects, while our detection threshold, though varying with the position in the fields, is typically about $R(\Delta\phi) \sim 22$. In Fig. 2 we show flux deviation vs. period for the the full set of short-period POINT-AGAPE variables, where solid circles mark those that were found by our analysis. In Fig. 3, we show the lightcurve of a POINT-AGAPE variable recovered within the OAB data, with its OAB extension.

3.2. Identified microlensing candidates

Since microlensing variations are quite unlikely to repeat, measuring a constant flux from follow-up observations provides further evidence that the previously observed signal has indeed been caused by microlensing. Our target fields contain three of the six can-

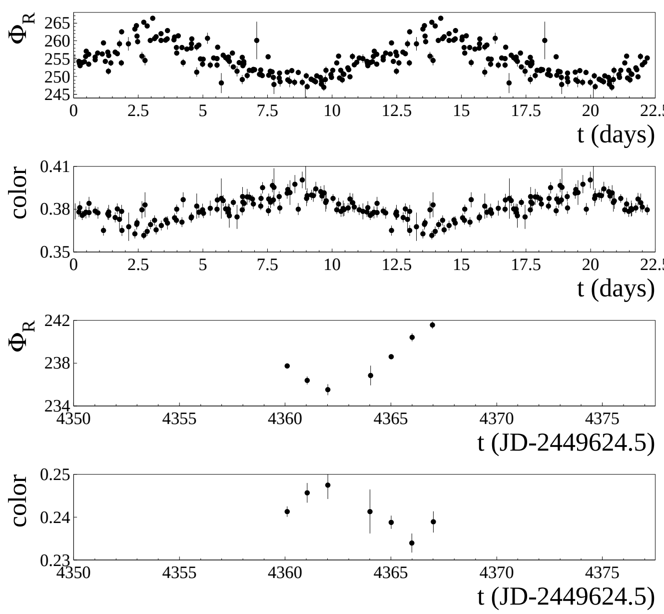

Fig. 3. The light curve of a POINT-AGAPE flux variation ($P = 11.14$ days and $R(\Delta\phi) = 21.1$), together with its extension in the OAB data. Top to bottom, the INT R and color light curves, folded by their period (for visual aid, two cycles are plotted); and the OAB R and color light curves. The "color" is evaluated as $-2.5\log(\phi_r/\phi_i)$, where ϕ is the observed flux. Flux is in ADU s^{-1}.

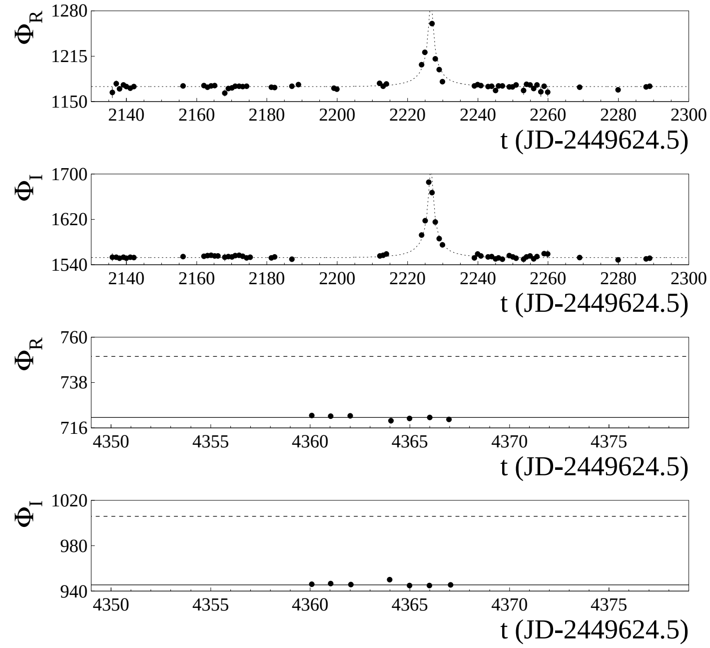

Fig. 4. The light curve of the POINT-AGAPE PA-S3 microlensing candidate (Paulin-Henriksson et al. 2003; Calchi Novati et al. 2005) together with its extension in the OAB data. In the INT data the dotted line is the best Paczyński (1986) fit; in the OAB data, the solid lines indicate the background level, while the dotted lines represent the flux deviation corresponding to the observed flux deviation at maximum for the POINT-AGAPE variation. The ordinate axis units are flux in ADU s^{-1}.

didates reported by the POINT-AGAPE collaboration (Calchi Novati et al. 2005), PA-N1, PA-S3 and PA-S7; beside PA-N1, two more among the 14 reported by the MEGA collaboration (de Jong et al. 2006), MEGA-ML-3 and MEGA-ML-15; beside PA-S3, the second candidate reported by the WeCAPP collaboration, WeCAPP-GL2 (Riffeser et al. 2003). *All* of the light curve extensions within our data set of the previous variations appear to be *stable*, namely, we do not observe any flux variation beyond the background noise level compatible with the observed microlensing flux variation. As an example, in Fig. 4 we show the PA-S3 light curve together with its extension in the OAB data.

3.3. A Nova like variation

Lastly, we discuss the result of a search for very bright flux variations ($R(\Delta\phi) < 19$). One flux variation survives this selection (Fig. 5), and this appears to be a nova-like variable (its extension on the POINT-AGAPE data set appears to be stable) located in RA=0h42m33s, DEC=41°10′06″ (J2000). We estimate the magnitude and color at maximum to be $R(\Delta\phi) \sim 17.5$ and $R - I \sim -0.1$. The rate of decline, about 2 magnitudes during the 7 nights of our observational period, puts this nova among the "very fast" ones in the speed classes defined in Warner (1989). The (strong) color evolution is rather unusual, as it got redder during descent. In the POINT-AGAPE nova

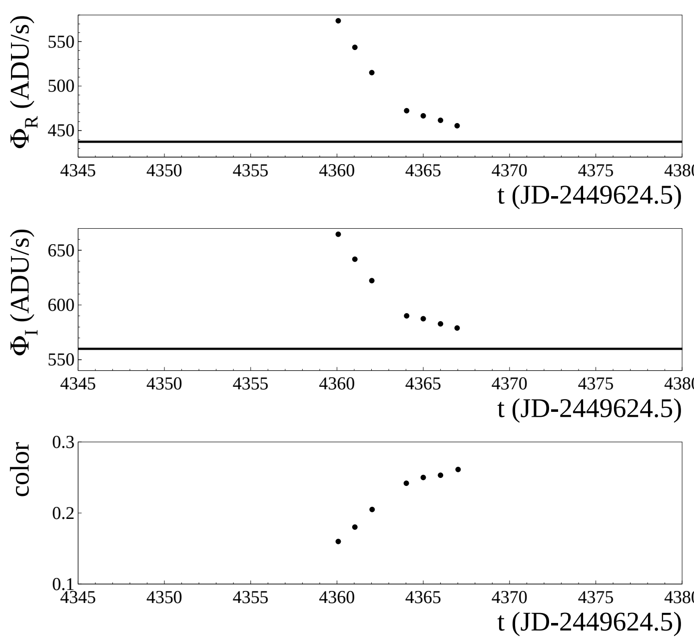

Fig. 5. The light curve of the Nova detected within the OAB data. Top to bottom, R, I bands and color data (as defined in Fig. 3) are shown. The solid lines (R and I data) indicate the estimate of the background level.

catalogue (Darnley et al. 2004), there was only one such object, PACN-00-07, showing a similar color evolution but also characterised by a fainter magnitude at maximum and a slower speed of descent.

The issue of the expected novæ rate in M31 is still a matter of debate. Darnley et al. (2006) evaluate a rate of ~ 38 (~ 27) novæ/years for the bulge (disc) respectively, while previous works pointed to somewhat smaller values (e.g. Capaccioli et al. 1989; Shafter & Irby 2001). Our detection of 1 nova during an overall period of 11 days is in any case in good agreement with these expectations (restricted to the bulge region only and using the first estimate, we derive an expected number of novæ of ~ 1.1).

4. The expected microlensing signal

To predict the number and characteristics of the expected microlensing signal for the different lens populations (Galactic halo and components of M31), we need both an astrophysical model for all the physical quantities that determine the microlensing events (which includes brightness profile, spatial mass density, velocity distributions, luminosity function for the sources, and mass spectrum for the lenses) and a model reproducing both the observational setup and the selection pipeline. Because of the huge parameter space involved, we use a Monte Carlo simulation to carry out this program. In particular, we make use of the simulation described in Calchi Novati et al. (2005), adapted to the OAB observational setup.

In Fig. 6 we report the results, obtained using the fiducial astrophysical model discussed in Calchi Novati et al. (2005), for the flux deviation at maximum and duration distributions expected for self-lensing events (the corresponding distributions for 0.5 $M_\odot$ MACHOs are almost indistinguishable) and, for both self lensing and MACHOs, the expected distance from the M31 center distribution. In particular we recover the well known results that most of the microlensing events are expected to last only a few days. We also stress the difference, already apparent within our relatively small field of view, between the spatial distributions due to luminous and MACHO lenses. The latter is much broader, implying that this diagnostic can be used to distinguish between the two populations. Note that here we are considering the distance-from-the-M31-center statistics rather than the expected asymmetry in the spatial distribution of M31 halo lenses (Crotts 1992; Jetzer 1994). The M31-center-distance statistic is sensitive to the different mass distributions of stars and dark matter, although it is a zeroth order approximation since it ignores the additional difference due to the expected asymmetry of the microlensing signal. We adopt this zeroth-order approach because the refinement needed to include the asymmetry information would require substantial additional analysis: as was pointed out by An et al. (2004), the study of variable stars demonstrates that differential extinction could induce a similar asymmetric signal on the spatial distribution of self-lensing events. Note also that our choice for the field position has not been chosen in order to optimise such an analysis, but rather to maximise the overlap with the fields of previous campaigns. Let us note that a real "second generation" pixel lensing experiment should cover a much larger field of view than ours, both to increase, for a given time baseline, the expected rate of events but especially in order to better disentangle the self-lensing signal from the MACHO signal.

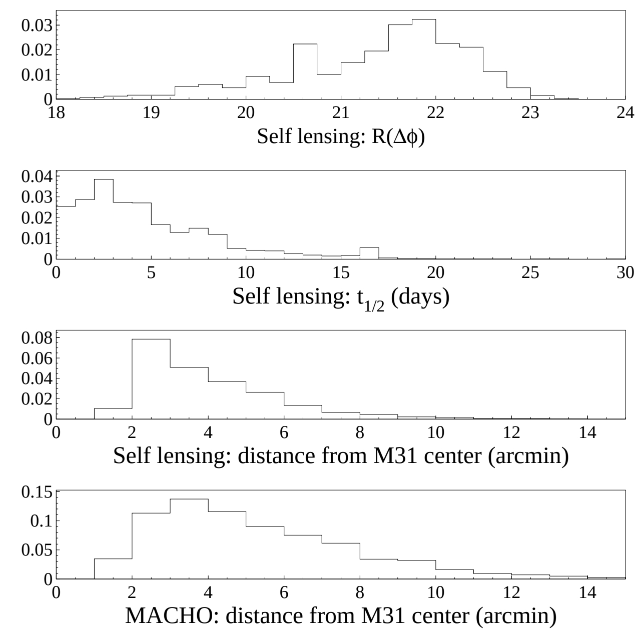

Fig. 6. Results of the Monte Carlo simulation: from top to bottom we show the histograms of the expected flux deviation at maximum, duration distribution for self-lensing events, and the distance (from the M31 center) distributions for self-lensing and for MACHOs. The units on the ordinate axes are the number of events.

To estimate the *number* of expected events, we reproduce the actual sampling of this pilot season and implement a basic selection for microlensing events (asking for the presence of a significant bump), and take into account the results of the analysis carried out in Sect. 3.1 by restricting to the subsample of $R(\Delta\phi) < 22$ variations. As a results, we predict ~ 0.17 self-lensing events and ~ 0.54 MACHOs (for full M31 and Galactic halos with 0.5 $M_\odot$ MACHO objects). As discussed in Calchi Novati et al. (2005), the predictions of the Monte Carlo simulation are quantifiable as "over-optimistic", so that these figures, for the given astrophysical model, should be taken as an *upper* limit to the actual number of expected events because we have not factored in the efficiency of the pipeline.

In order to increase the available statistics we need a longer time baseline. An aspect here deserves to be stressed. As the expected duration of the events we are looking for is of the same order of the length of our present baseline, because of "boundary" effects, the number of expected events should increase more than linearly with the overall baseline length (of course, this is no longer true

as soon as the baseline is long enough). This holds under the condition that no gaps are introduced into the sampling, clearly showing the importance of an appropriate observational strategy. For example, for a full two-month campaign we predict, again for the sub sample of $R(\Delta\phi) < 22$ variations, ~ 1.3 (5.1) self-lensing (0.5 $M_\odot$ MACHO) events, respectively. Finally, we note that we have obtained similar results within a parallel analysis carried out following the approach outlined in Ingrosso et al. (2006a,b).

As for the astrophysical model, we recall that de Jong et al. (2006), using a different model for the luminous components of M31, obtained a significantly higher expected contribution of the self-lensing signal relative to that evaluated with the fiducial model discussed in Calchi Novati et al. (2005), which we are also using in the present analysis. Hence, the full-fledged campaign that we are planning will be important for understanding the disputed issue of M31 self-lensing as well as MACHO dark matter.

5. Conclusions

Based on pilot season observations of M31 during 11 consecutive nights in September 2006 and a Monte Carlo simulation for the expected properties of microlensing events caused by lenses in the Galactic halo or M31, respectively, we have shown the feasibility of an extended campaign with the 1.5m Loiano telescope being able to resolve the current puzzle of the origin of microlensing events involving extragalactic sources.

In particular, we were able to identify known variable stars from our data thanks to the tight sampling and despite the short time range covered. Reported microlensing candidates within our field of view have shown no further variation, therefore the microlensing interpretation was confirmed. Moreover, a nova variable showed up in our data.

As for the microlensing signal, we have stressed the importance of an appropriate sampling for the observations, and discussed the results of a Monte Carlo simulation of the present experiment. In particular, we have shown how the expected spatial distribution for self-lensing and MACHO events can allow us to disentangle the two contributions. Finally, we have provided an evaluation of the expected number of microlensing events for the present pilot season and discussed quantitatively the possible output of a longer baseline campaign.

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